Technology Development and Industry Participation in the *Lynx* High Definition X-ray Imager (HDXI)

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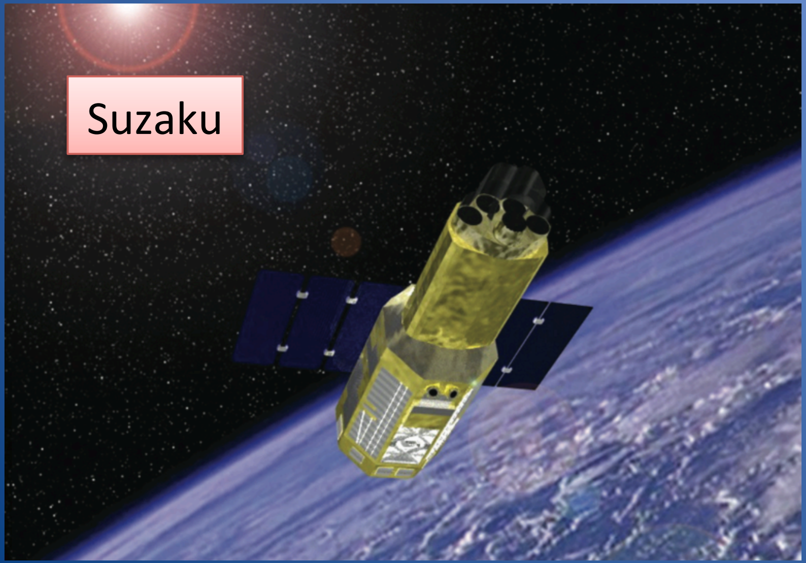
Current and Future Si sensors in X-ray Astronomy



Chandra/ACIS Image of Centaurus A

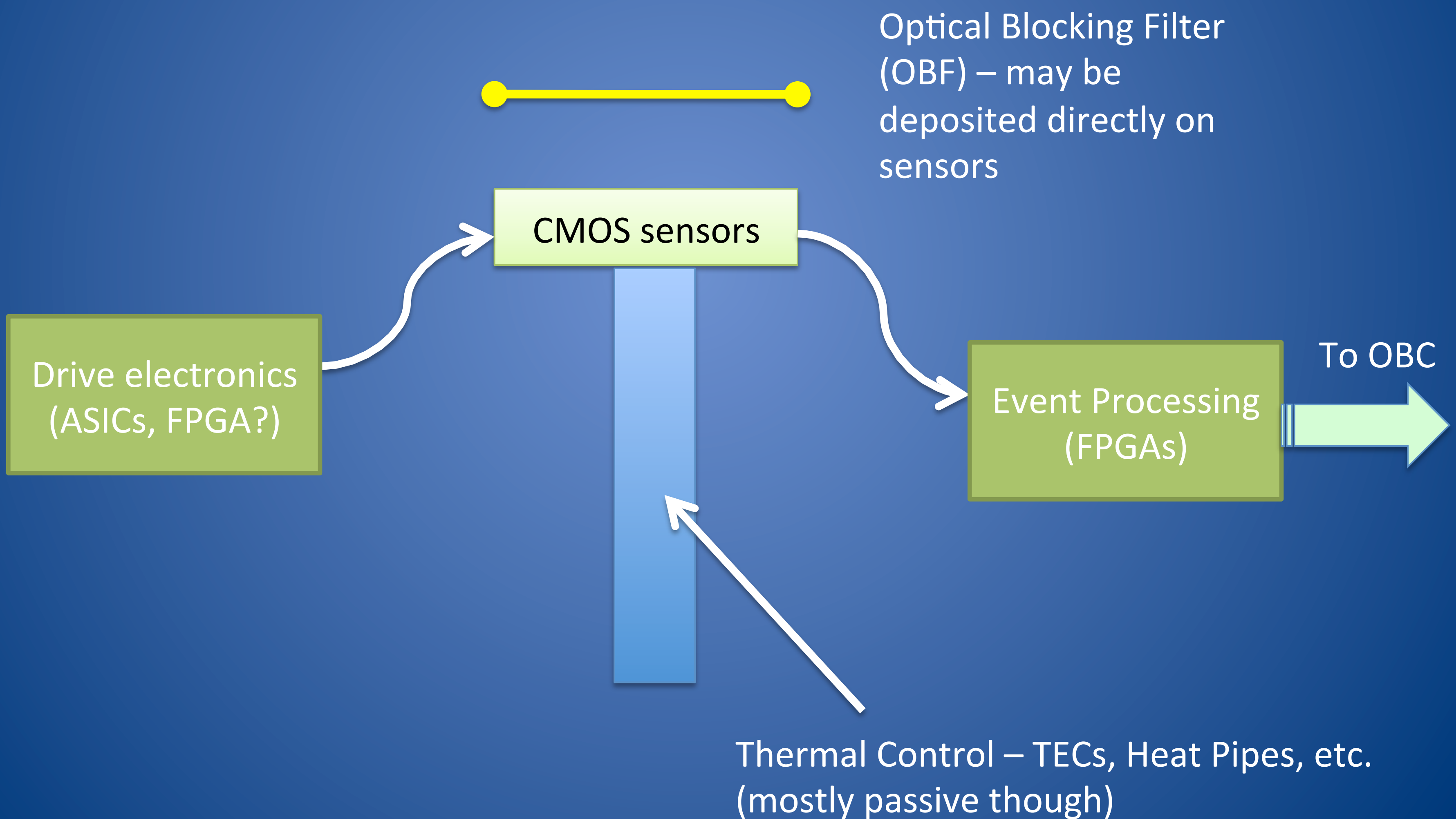
Nearby radio galaxy observed with Chandra

•Color denotes X-ray energy: red-> lower energy, blue/white-> higher energy

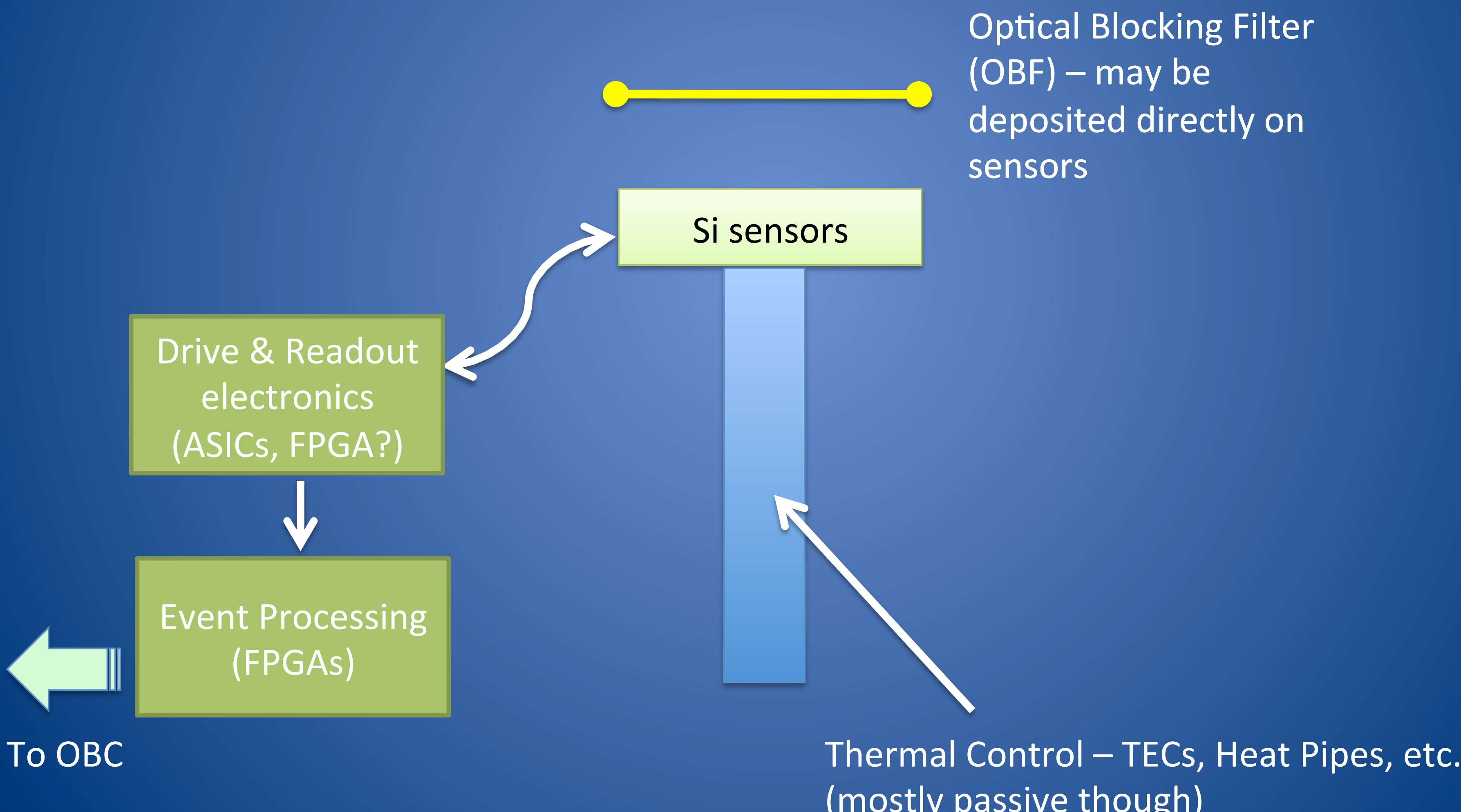
Current and Future Si sensors in X-ray Astronomy

- Every X-ray observatory launched in the past 20 years has flown CCDs
- Many advantages of this technology for X-ray imaging spectroscopy
  1. High QE over soft X-ray bandpass
  2. Efficient (>99%) charged-particle rejection
  3. Moderate energy resolution ($E/\Delta E \sim 50$ at 5.9 keV)
  4. Small pixels well-matched to PSF of X-ray optics
- Mode of operation different than optical/IR imager
  1. Operate in single photon counting mode – detect individual photons
  2. Continuous readout of sensor to avoid pileup (frame time – 100s of ms to secs)
  3. Only X-ray events telemetered to ground
- Challenges for megapixel sensors for next generation X-ray observatories
  - Desire frame rates of 10^2-10^3 of frames per second with low noise
  - Adequate radiation tolerance
  - High speed windowing with little or no dead time
  - Very high-performance backside treatment for complete charge collection

Schematic Block diagram of HDXI



Schematic Block diagram of HDXI



Status, Future Developments, and Fundamental Trade-offs for the sensors and electronics of the HDXI

Basic requirements – *to be modified by STDT*!

HDXI Parameters/ Requirements	
Energy Range	0.2 – 10 keV QE > 90% (0.3-6 keV), QE > 10% (0.2-9 keV)
Field of View	22' × 22' (4k × 4k pixels)
Pixel size	≤ 16 × 16 micron (≤ 0.33 arcsec)
Read noise	≤ 4 e^-
Energy resolution	37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)
Frame rate	> 100 frame/s (full frame) > 10000 frame/s (windowed region)
Radiation tolerance	10 years at L2

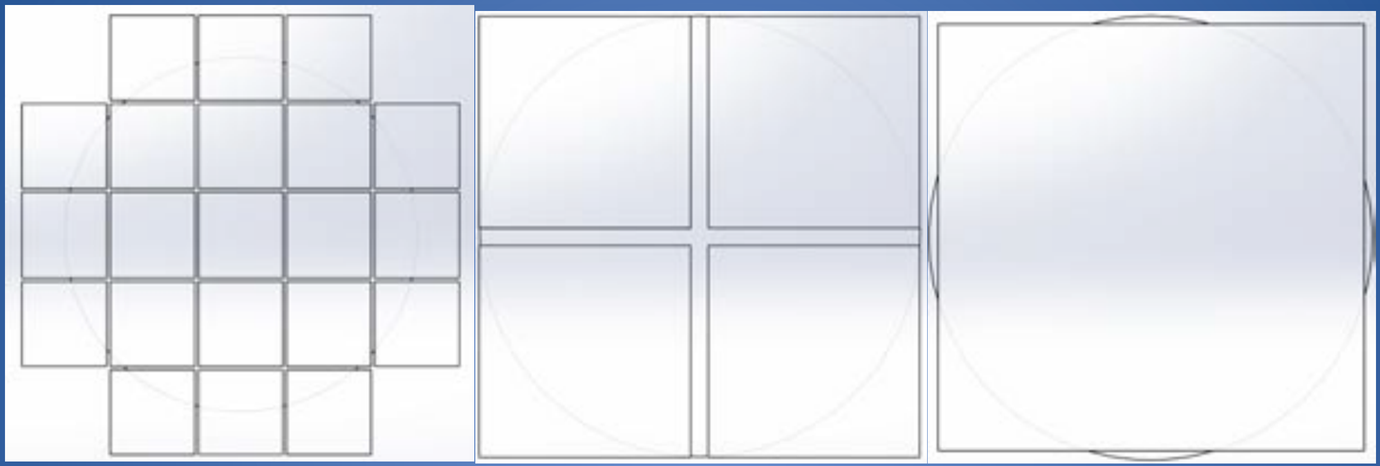
Three active pixel sensor technologies currently under discussion by IWG

- Digital CCDs (LL/MIT)
- Hybrid CMOS (Teledyne/PSU)
- Monolithic CMOS (Sarnoff/SAO/MPE)

Additional Sensor Developments:

- High Speed Event Processing Electronics
- Ge detectors (?)
- Event-driven detection (?)
- Thick devices with sub-pixel resolution

Notional Detector Layout Options



Notional schematic layouts of detector focal plane with 3 options: (a) 21 detectors with 1024x1024 pixels, (b) 4 detectors with 2048x2048 pixels, and (c) 1 detector with 4096x4096 pixels. The multiple detector options can be tilted to accommodate a curved focal plane surface.

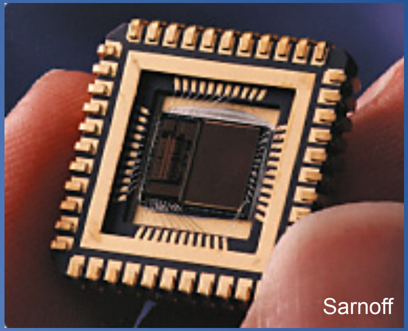
Based on initial ray tracing studies, the curved surface appears to be needed to fully realize the angular resolution offered by mirrors with subarcsec resolution.

→ *It seems likely that the focal plane will be tiled with multiple detectors to match the optimum focal surface.*

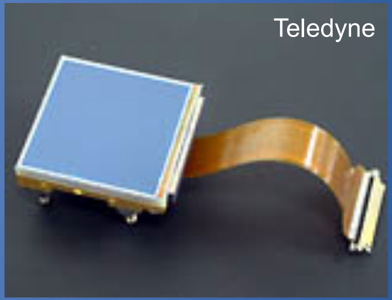
Some discussion among STDT for larger HDXI focal plane

3 Different Sensors Approaches

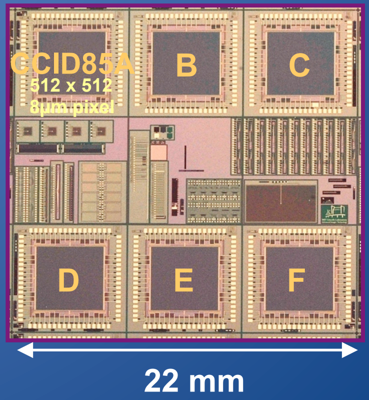
- Monolithic CMOS Active Pixel Sensor
  - Single Si wafer used for both photon detection and read out electronics
  - Sarnoff/SAO and MPE



- Hybrid CMOS Active Pixel Sensor
  - Multiple bonded layers, with detection layer optimized for photon detection and readout circuitry layer optimized independently
  - Teledyne/PSU



- Digital CCD with CMOS readout
  - CCD Si sensor with multiple parallel readout ports and digitization on-chip
  - LL/MIT



Digital CCD

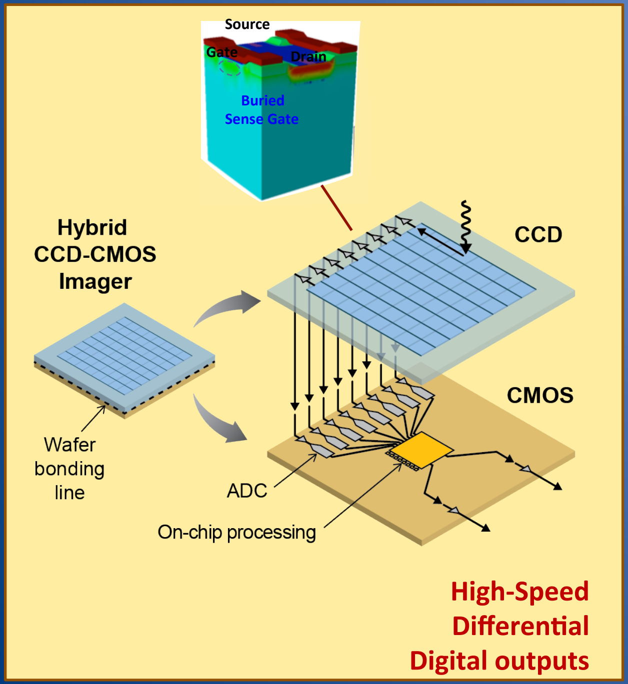
MIT Lincoln Laboratory

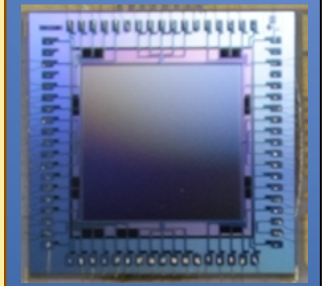
Concept: Hybrid CCD-CMOS Imager

- High Frame Rate
  - Very fast outputs (~5 MHz)
  - Integrated parallel signal chains
- Low Noise: High-responsivity, sub-electron read noise amplifier
- Low-power: CMOS-compatible CCD

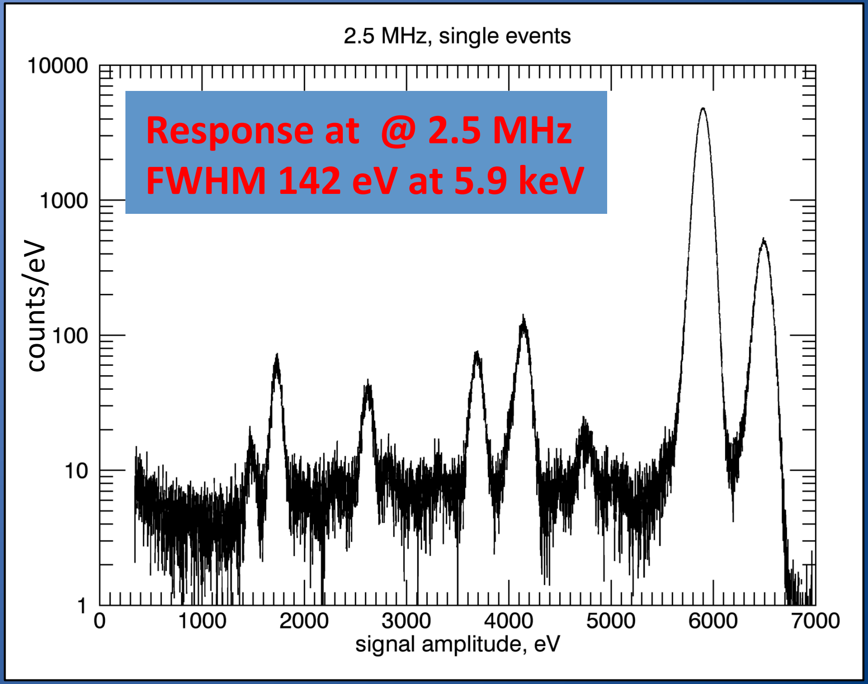
Current status: CMOS-compatible CCD with conventional amplifier:

- Noise < 7 e^- RMS @ 2.5 MHz (25x faster than Chandra)
- Excellent charge transfer at CMOS levels (± 1V; ~same clock power/area as Chandra @ 25x higher rate)
- 8 µm pixels (oversamples Lynx PSF)



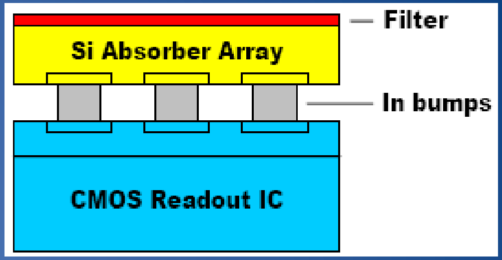


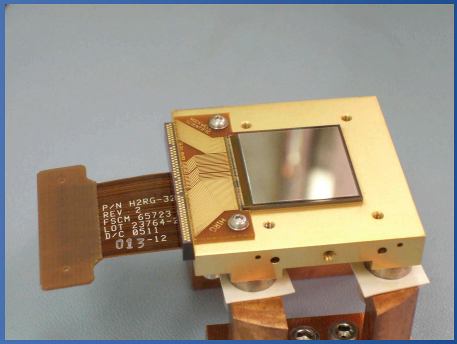
Test Device



CMOS Hybrid Sensors (PSU/Teledyne – PI: A Falcone)

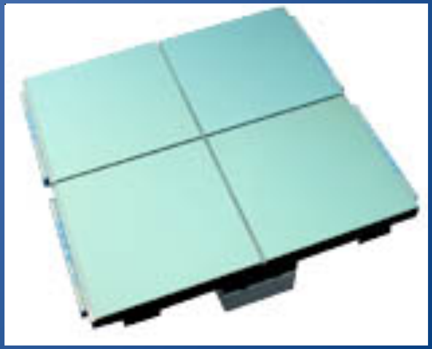
- Silicon detector array and readout array bump-bonded together
  - Allows separate optimization of detector and readout
  - Readout electronics for each pixel
  - ***Optical blocking filter deposited on detector***
- Based on IR detector technology with heritage from JWST and high TRL/flight-heritage from OCO
- Back illuminated with 100-300 micron fully depleted depth
  → ***excellent QE across 0.2-15 keV band***
- Inherently **radiation hard**, with no charge transfer across detector
- Up to 4k×4k pixels, with abuttable designs
- ***High speed*** (10 Mpix/sec × N outputs) with ***low-power***
- Read noise (~5-10 e$^-$) needs improvement. Fano-limited performance is expected, with work in progress.





Selection of recent progress

- Inter-pixel ***crosstalk eliminated*** with CTIA amplifiers
- ***Event-driven readout*** on 40 µm pixels (very fast frame rates)
- New test devices with small ***(12.5 µm) pixels*** *and* ***in-pixel CDS***, fabricated and tested to have ~5 e- readnoise

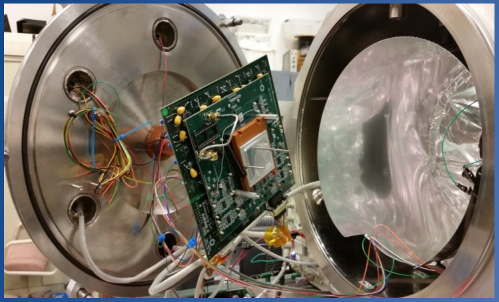


Future work:

- (1) scaling small-pixel test design up to larger detector, (2) reduce read noise further with improved component tolerance, while maintaining low read noise at high readout rates, (3) attempting to implement event-driven readout in smaller pixels, (4) investigating sub-pixel centroiding in large pixels

Hybrid CMOS X-ray detectors, Falcone et al.

Monolithic CMOS Sensors (SAO/ Sarnoff – PI: A. Kenter)



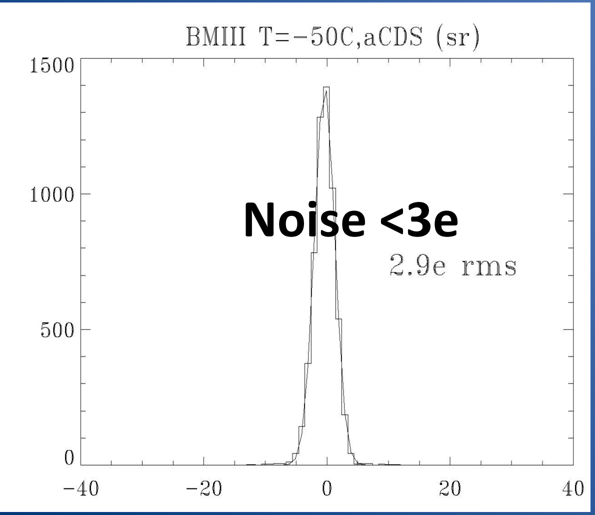
BI Monolithic device with Optical Blocking Filter in SAO test chamber

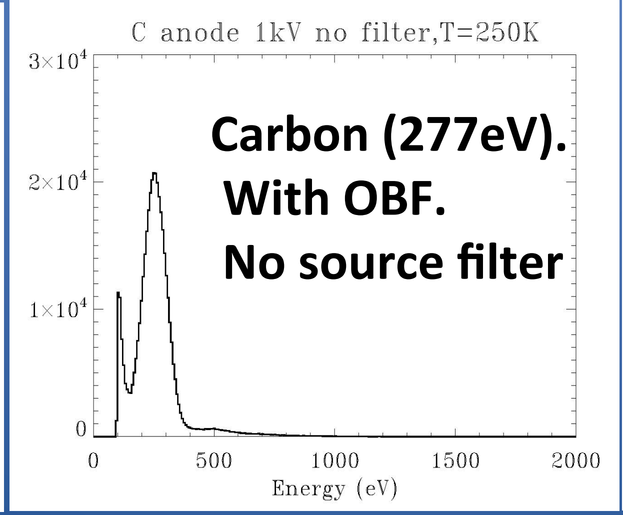
- 1k by 1k, 16μm pitch devices.
- High sensitivity ~135μV/e pixel (<Carbon x-ray> produces ~10mV @ pixel!)
- Row-at-a-time on chip CDS (1k by 1k device can CDS process 1k pixels in ~20μ sec)
- Modest cooling requirements. Back thinned by Mike Lesser @U. of Arizona
- High through-put mitigates dark current and out-of-band optical light

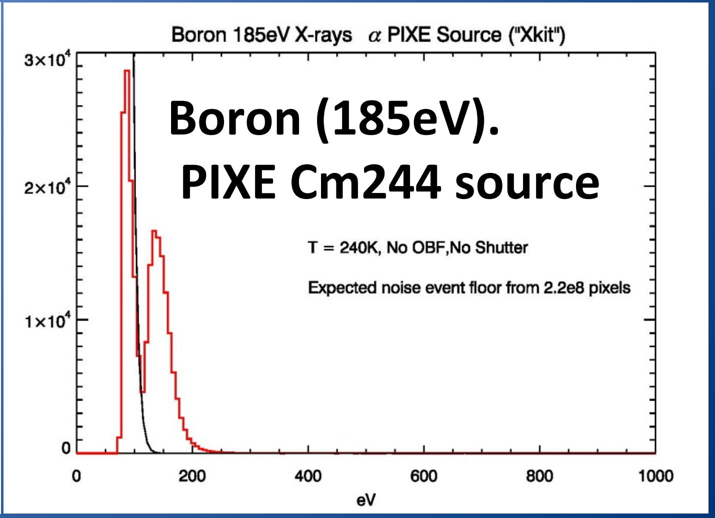
Pixel size and soft response well matched to envisioned Lynx optic PSF

2016 APRA: Demonstrate PMOS devices (photo holes vs photo electrons)

- Lower read noise (~1h rms)
- "No" Random Telegraph Signal (RTS) noise
- Lower recombination of photo charge







Current State of the Art

- Each of the sensor technologies presently meets some of the expected requirements.
- No single sensor meets them all – lots of work to do!

Key improvements over ACIS and EPIC

- Orders of magnitude higher frame rates (>100 full-frame/sec, >10000 subframe/sec)
- Significantly improved radiation hardness
- Fully addressable (i.e. high speed windowing)
- Near Fano-limited resolution over entire bandpass
- Lower power
- Near room temperature operation
- Large format (up to 4Kx4K) abuttable devices

Key sensor trade-offs

1) Pixel size
   - Small pixel size to oversample PSF decreases energy resolution – requires better noise and faster readout
   - Small pixels increases number of sensors required to fill focal plane
   - Larger pixels could be used to perform sub-pixel centroiding (this would require deep depletion and multi-pixel events)
2) Deep Depletion
   - Thick devices improve QE above 5 keV but degrade energy resolution below 1 keV
3) Higher Frame Rates
   - Mitigates pileup and *may* improve background rejection, but increases complexity and power of read out electronics

Technical Challenges

- **Quantum Efficiency**: Hybrids have achieved the depletion depths required for high quantum efficiency across the X-ray band, but the monolithic devices still need to make further developments to achieve these depletion depths
- **Read Noise**: Monolithic architectures have achieved low read noise, but hybrids still need to progress further to achieve < 4 e^-
- **Small Pixels/Aspect Ratio**: All devices have achieved small pixel sizes, but further development is needed to do this while retaining other advantages and while limiting impacts of increased charge diffusion due to the increase in the aspect ratio of pixel depth-to-width
- **Rate**: While higher frame rates are already possible with APSs, relative to CCDs, significantly more development is needed to handle the data from these increased frame rates at the focal plane level and to achieve the required read noise while simultaneously achieving fast frame rates for the long-term mission requirements (>100 frame/sec for >16 Mpix cameras)
- **Near Unity QE down to** 0.15 **keV:** STDT science discussions suggest emphasise on soft (<1 keV) efficiency as a key driver. This will require near unity efficiency from the sensor and OBF combination.

Additional Technical Development from Industry Partners

- Advanced sensor development
- Low, power, high-speed, radiation-tolerant ASICs for driving sensors
  - 10-1000 1024x1024 frames s^{-1}
- Low noise, low-power, multi-channel signal processing chains
  - 10-1024 chains per sensor
- High-performance sensor entrance window (‘back’ surface) passivation for complete charge collection
  - Fano-limited energy resolution at low energies
- High-speed FPGAs for real-time event detection and processing
  - Handle high frame rates to detect ‘islands’ of charge

Additional Technical Development from Industry Partners

- Instrument thermal system design for focal plane and electronics
  - Depends critically on sensor technology – could be near room temperature or -120 C
- Technology for efficient IR/optical/UV blocking filters with maximum soft (E ~ 0.2 keV) X-ray transmission
  - Eliminate polyimide and C edge in response
- Shielding design for minimum charged-particle background
  - Graded-Z design (?)
- Mechanism design for doors, vents and filter wheels
  - Mechanisms for class A/B mission
- **Inputs and guidance on technology development plan**

Future work of *Lynx* IWG HDXI team:

- Continue technology development
  - Improve energy resolution, QE, frame rate, and dark current of sensors to achieve XRS requirements
  - Develop FPGA-based event processing electronics (PI: Burrows)
  - Revise planned timeline and budget to achieve TRL 5
    and then TRL 6 for the detectors
- Upcoming Studies for *Lynx* HDXI
  - Contribute to Technology Roadmap (we could *definitely* use industry assistance in this area!)
  - Support ACO costing/mission design for the STDT
  - HDXI-specific IDL at GSFC (fall 2017)
  - Define path to full instrument TRL 5 & TRL 6
  - Revisit cost estimates for full HDXI instrument

GOAL: Receive the blessing of the 2020 Decadal Review and start building the mission!